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Review article

Opportunities for Optimising the CORS Network in Uzbekistan: Proposals Based on Bibliometric Analysis

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Abstract
This study examines the optimisation of Continuously Operating Reference Station (CORS) networks through a combined bibliometric and spatial analysis approach, with particular reference to Uzbekistan as an illustrative case. A total of 522 publications were reviewed, of which 53 were identified as most relevant for detailed thematic analysis, as they provided insights into global research trends, methodological approaches, and applications in geodetic network design. To demonstrate how these approaches can be applied in practice, a simplified GIS-based spatial analysis was conducted in ArcGIS Pro to evaluate the distribution of existing CORS stations in Uzbekistan. A 40 km geodetic buffer was used as a representative distance derived from commonly reported baseline ranges in the literature (30-70 km). It should be emphasised that such a buffer-based approach only reflects spatial coverage and does not account for positioning accuracy, network geometry, or GNSS error sources. The results indicate uneven spatial coverage, with relatively dense station distribution in central and eastern regions, while western areas remain less represented. This finding is presented as a preliminary spatial observation rather than a validated assessment of network performance. Overall, the study does not aim to define optimal station spacing, or to provide a full technical evaluation, but rather to synthesise existing knowledge and demonstrate how simplified spatial methods can support initial planning. Future work should focus on integrating these insights with empirical GNSS data and advanced optimisation techniques for more robust network design.

Keywords: CORS network; GNSS optimisation; Geodetic infrastructure; Uzbekistan; Coverage analysis; Bibliometric analysis.

1. Introduction

CORS networks consist of permanent GNSS receivers that continuously collect satellite data, supporting precise positioning, geodetic control and monitoring of tectonic or geophysical changes. They enhance the accuracy, reliability and homogeneity of geodetic networks, often replacing or densifying traditional ground control points (Abdallah & Agag, 2022; Ayodele *et al.,* 2020; Dardanelli *et al.,* 2020; Mahdi & Ahmed, 2024; Schwieger *et al.,* 2019; Snay & Soler, 2008). CORS data are vital for defining and maintaining national geodetic reference frames and for applications in engineering, hazard analysis and infrastructure development (Abdallah & Agag, 2022; Ayodele *et al.,* 2020; Chhetri *et al.,* 2024; Snay & Soler, 2008).

Geodetic networks play an important role in cartography, construction, cadastre, geographic information systems, navigation and scientific research (Figure 1). They are one of the fundamental elements of modern infrastructure, serving to establish a unified coordinate and height system at the national level. In addition, the development of CORS networks provides significant advantages for the agricultural sector, particularly in irrigation and land reclamation (melioration) (Yurdakul & Kalayci, 2022). High-precision GNSS positioning supported by CORS enables accurate field measurements, optimisation of irrigation canals, monitoring of soil subsidence, and efficient management of water resources (Gokdas & Ozludemir, 2021). This contributes not only to the sustainable use of natural resources, but also to improving productivity and environmental stability in agricultural landscapes.

The process of designing and optimising geodetic networks is a crucial task aimed at finding the most efficient solutions by balancing network configuration, the number and location of observations, accuracy, reliability and cost. Modern approaches integrate classical mathematical models with evolutionary algorithms. In geodetic network design, the main challenges are categorised into zero-order design (datum definition); first-order design (network configuration); second-order design (observations and their weights); and third-order design (improvement of the existing network). At each stage, accuracy, reliability and cost are considered as the primary criteria (Abd Allah & Wang, 2022; Amiri-Simkooei *et al.,* 2012; Grafarend & Sansò, 1985; Schmitt, 1982).

In recent years, evolutionary algorithms such as genetic algorithms, particle swarm optimisation, and simulated annealing have been increasingly applied in geodetic network optimisation. These methods facilitate the rapid and efficient identification of optimal solutions in large and complex networks, with particular effectiveness in GNSS networks and deformation monitoring (Al Shouny, 2025; Berné & Baselga, 2004; Maksimović *et al.,* 2019; Michal & Štroner, 2024; Yetkin & Inal, 2015).

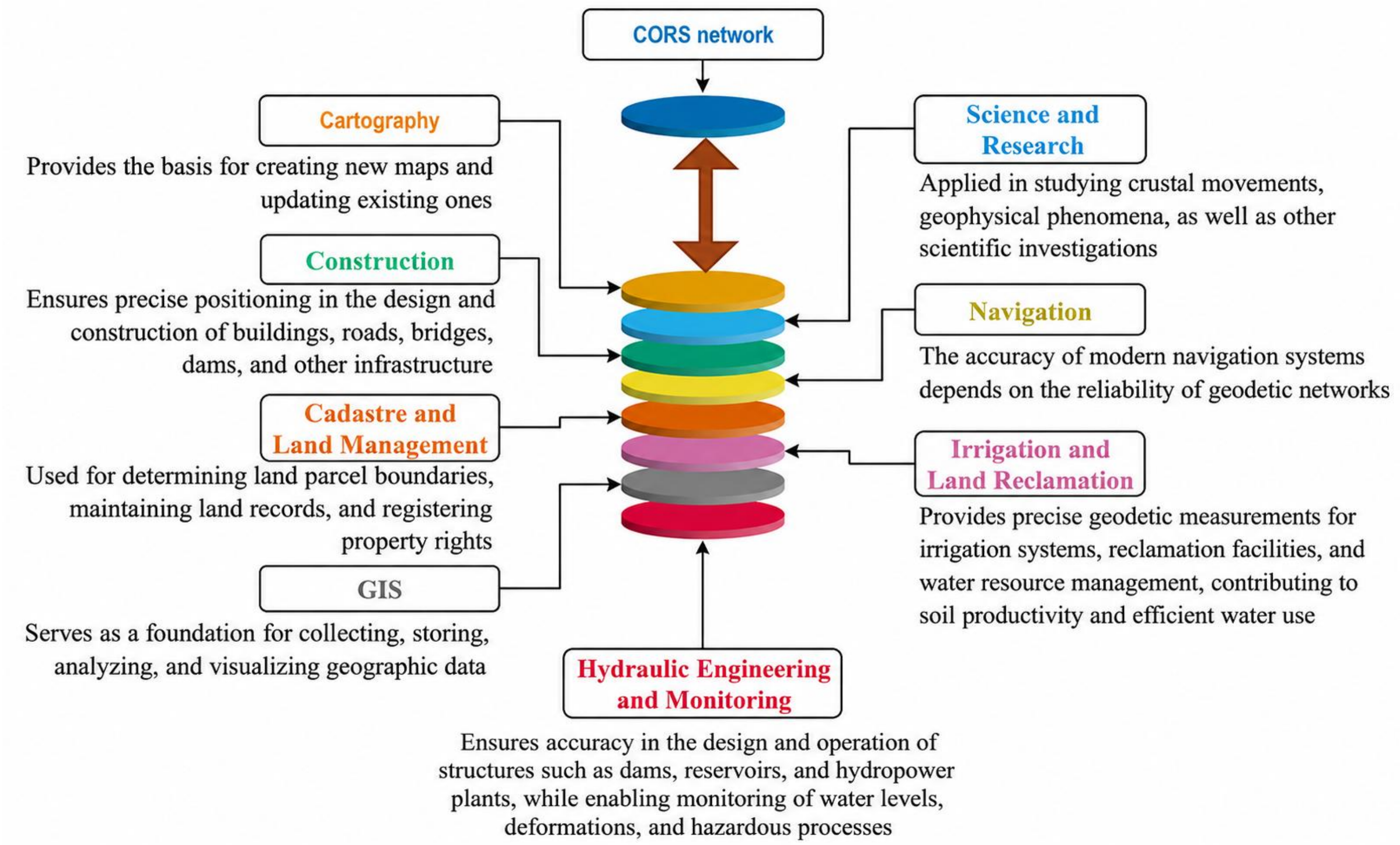

Figure 1. Integration of geodetic networks with other fields.

Furthermore, the use of multi-criteria optimisation models, which simultaneously account for accuracy, reliability and economic efficiency, enhances the overall design of geodetic networks. In this context, mathematical programming techniques (linear, quadratic and nonlinear) combined with automated algorithms are employed to determine the optimal configuration and observations (Abd Allah & Wang, 2022; Kuang & Chrzanowski, 1992; Michal & Štroner, 2024).

Determining the optimal spacing between CORSs are essential for balancing positioning accuracy, spatial coverage and economic efficiency. Previous studies indicate that medium baseline distances, typically in the range of 30-70 km, provide a practical compromise for most GNSS networks; however, this range may vary depending on climatic conditions, terrain characteristics and application requirements (C. Yu *et al.,* 2020: Rahman *et al.,* 2023).

In regions with CORS stations spaced around 100 km apart, ionospheric correction accuracy can reach 2-5 cm, supporting high-precision applications such as surveying and mapping (Dao *et al.,* 2022). Networks with 100-200 km spacing can still achieve centimetre-level accuracy, although performance may degrade during periods of high ionospheric activity or in low-latitude regions (Dao *et al.,* 2022). When station spacing exceeds 200 km, accuracy decreases significantly and may not support reliable corrections (Dao *et al.,* 2022; I. Naibbi & S. Ibrahim, 2014).

Comparative studies from different regions highlight the impact of inter-station spacing on CORS network performance. In Turkey, local CORS networks with shorter inter-station distances have demonstrated higher vertical accuracy and faster ambiguity resolution, while increasing station spacing leads to reduced FIX solution ratios and longer ambiguity resolution times (Atiz *et al.,* 2022; Gökdaş & Özlüdemir, 2022). Similarly, studies in Malaysia comparing short (0-30 km), medium (30-70 km), and long (70-180 km) baselines indicate that medium baselines provide the most effective balance between positioning accuracy, ambiguity resolution (with success rates exceeding 50%) and cost-effectiveness (Rahman *et al.,* 2023).

These findings indicate that while medium inter-station distances are generally effective, their performance depends strongly on regional conditions such as atmospheric variability, terrain complexity and infrastructure availability. Therefore, there is no universally optimal spacing strategy, and CORS network design must be adapted to local conditions.

Uzbekistan has been developing its geodetic infrastructure since 2005 through the implementation of multi-level geodetic networks, including reference geodetic points (RGPs) and satellite-based networks (SGN-0 and SGN-1). Since 2018, approximately 50 CORS stations have been established, supporting real-time and post-processed GNSS positioning, together with the development of a national geocentric coordinate system (Fazilova *et al.,* 2021; Suyunov *et al.,* 2023).

However, despite this progress, access to continuous GNSS observational data remains limited, and comprehensive optimisation studies are still insufficient. In practice, simplified approaches such as buffer-based spatial analysis are often used, although they do not fully represent network performance or accuracy.

This study is designed as a bibliometric and conceptual review rather than a full empirical GNSS network performance assessment. While numerous studies have proposed advanced optimisation models for CORS network design, their practical implementation often depends on the availability of high-quality GNSS observations, computational resources and stable infrastructure. As a result, such approaches are not easily transferable to data-limited regions.

In this context, a clear gap exists between theoretically robust optimisation models and their practical applicability in developing countries. To address this gap, this study integrates bibliometric insights with a simplified GIS-based spatial analysis framework. By analysing 132 CORS stations in Uzbekistan, the study demonstrates how such an approach can support preliminary network planning and identify spatial coverage gaps under data-constrained conditions. The study proposes a practical decision-making approach for the preliminary planning of CORS networks in such data-limited scenarios.

2. Methods

A bibliometric and content analysis of global scientific publications on geodetic network optimisation was conducted. For this purpose, Scopus, a major international scientific database, was selected. This is widely recognised within the academic community and regularly indexes high-impact journals and conferences. The search covered publications up to the end of 2024, with the results refined through thematic filtering to ensure relevance to environmental sciences and computer science domains.

The search strategy was developed based on strict inclusion criteria. Within the Scopus database, the following query formula was applied: (TITLE-ABS-KEY (" geodetic network*" OR "geodesy network*" OR "geodetic control network*" OR "geodetic reference network*" OR "GNSS network*" OR "GPS network*" OR "satellite positioning network*" OR "CORS network*" OR "continuously operating reference station*" OR "RTN network*" OR "real-time kinematic network*" OR "permanent GNSS station*" OR "DGPS" OR "RTK network*" OR "differential GNSS network*" OR "VRS network*")) AND (TITLE-ABS-KEY ("optimization" OR "optimal placement" OR "coverage" OR "network design" OR "accuracy improvement" OR "adjustment" OR "error modelling" OR "simulation" OR "spatial analysis" OR "GIS" OR "geoinformatics" OR "remote sensing integration" OR "geospatial modelling" OR "visualization")) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (LANGUAGE , "English"))

The search criteria applied ensured the retrieval of publications directly related to the optimisation of CORS station networks, while excluding studies from unrelated fields such as medicine or chemistry. In the initial stage, a total of 522 articles were identified. Through semantic filtering based on abstracts, titles and keywords, irrelevant records were eliminated. As a result, a clean corpus of 53 publications explicitly addressing CORS network optimisation was formed. While bibliometric analysis was conducted on the full set of 522 articles, thematic literature analysis was performed on the refined corpus of 53 studies (Figure 2).

The bibliometric analysis was implemented in several stages. First, the annual publication dynamics were examined to identify the formation and development trends of scientific interest in the topic. Second, a country-level analysis was conducted to determine the most productive nations in terms of publication output. Third, publication platforms were assessed to identify the most active journals and conferences. Fourth, the role of funding organisations was evaluated, revealing the leading institutions supporting research in this area. Fifth, author and affiliation networks were analysed to highlight the researchers and institutions contributing significantly to the advancement of the field. Finally, disciplinary distribution was examined, with five priority scientific domains identified based on percentage representation.

A separate analysis was conducted specifically for Uzbekistan. The same 53 publications identified earlier were examined in detail, and their thematic content was classified into five main categories: design and optimisation of geodetic networks; atmospheric modelling (troposphere/ionosphere) and water vapour estimation; robust adjustment and resilience against erroneous measurements; computational efficiency and emerging optimisation paradigms; and applied case studies and monitoring. This categorisation highlights the dominant directions of research directly applicable to the optimisation of GNSS/CORS networks in the region (Figure 2).

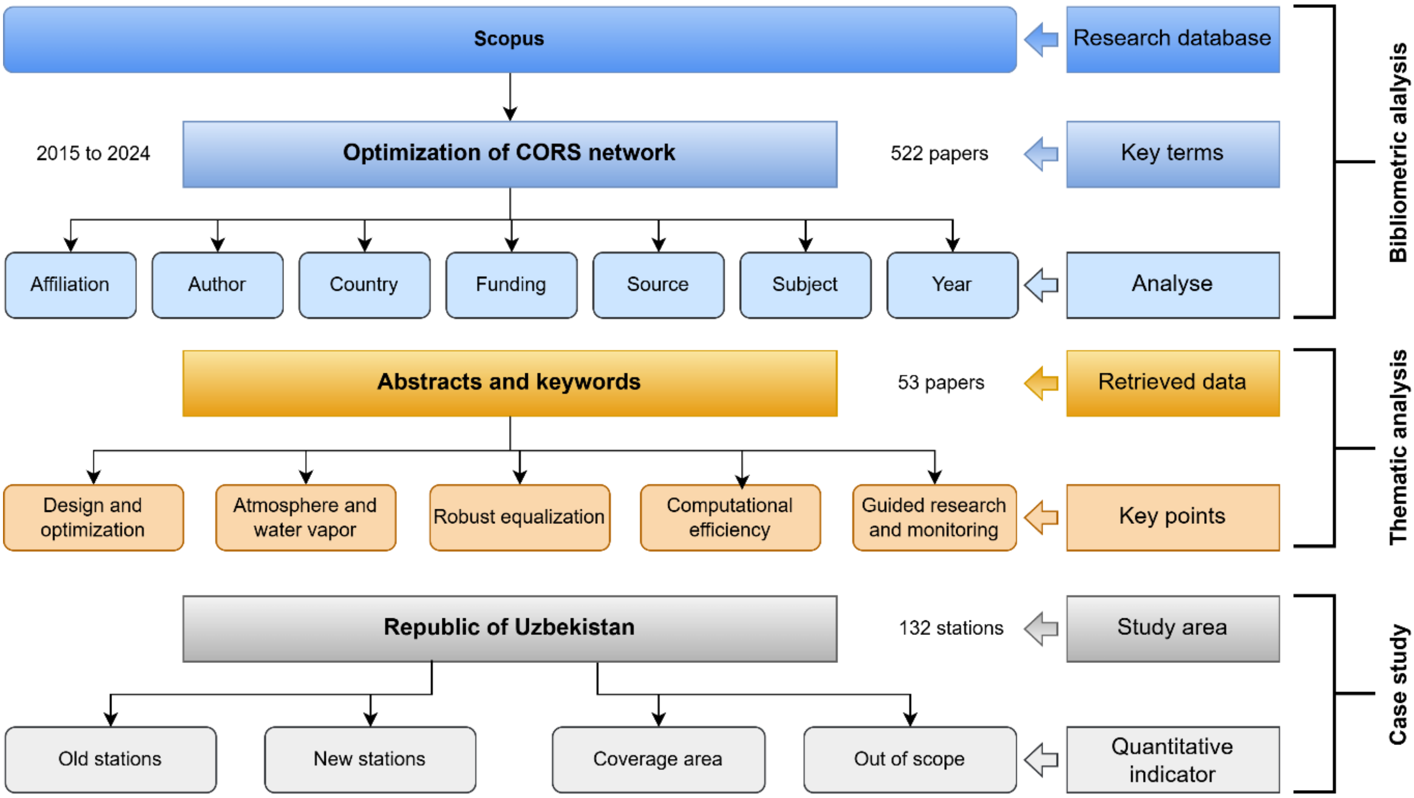

Figure 2. Flowchart.

Overall, this methodology ensures a systematic overview of the field while distinguishing between general research trends and domain-specific insights related to CORS network optimisation.

3. Results and Discussion

3.1. Bibliometric Analysis

Our study provides a comprehensive synthesis of previous research on the optimal deployment of geodetic networks. Over the past decade, the number of publications has fluctuated considerably (Figure 3a). The lowest output was recorded in 2016 (~35 publications), followed by a steady increase between 2017 and 2020. In 2024, a significant rise occurred again, reaching 65 publications. This trend clearly reflects the growing interest in the topic.

In terms of geographical distribution, the highest number of studies was published in China (102 papers), followed by the United States (73) and Germany (45) (Figure 3b). Regarding the host journals, the largest share of contributions appeared in the Journal of Geodesy and the Journal of Surveying Engineering (~30 publications each) (Figure 3c). In addition, leading high-impact journals such as Remote Sensing, Survey Review, GPS Solutions and Geophysical Journal International also ranked among the most active outlets. This indicates that research on CORS network optimisation is primarily disseminated within the domains of geodesy and remote sensing.

Among funding sources, the National Natural Science Foundation of China (NSFC) is the clear leading contributor, supporting more than 70 publications (Figure 3d). The gap between the first and second most active funding bodies is substantial, with a difference of nearly 50 papers, highlighting NSFC's dominant role in advancing research on CORS network optimisation.

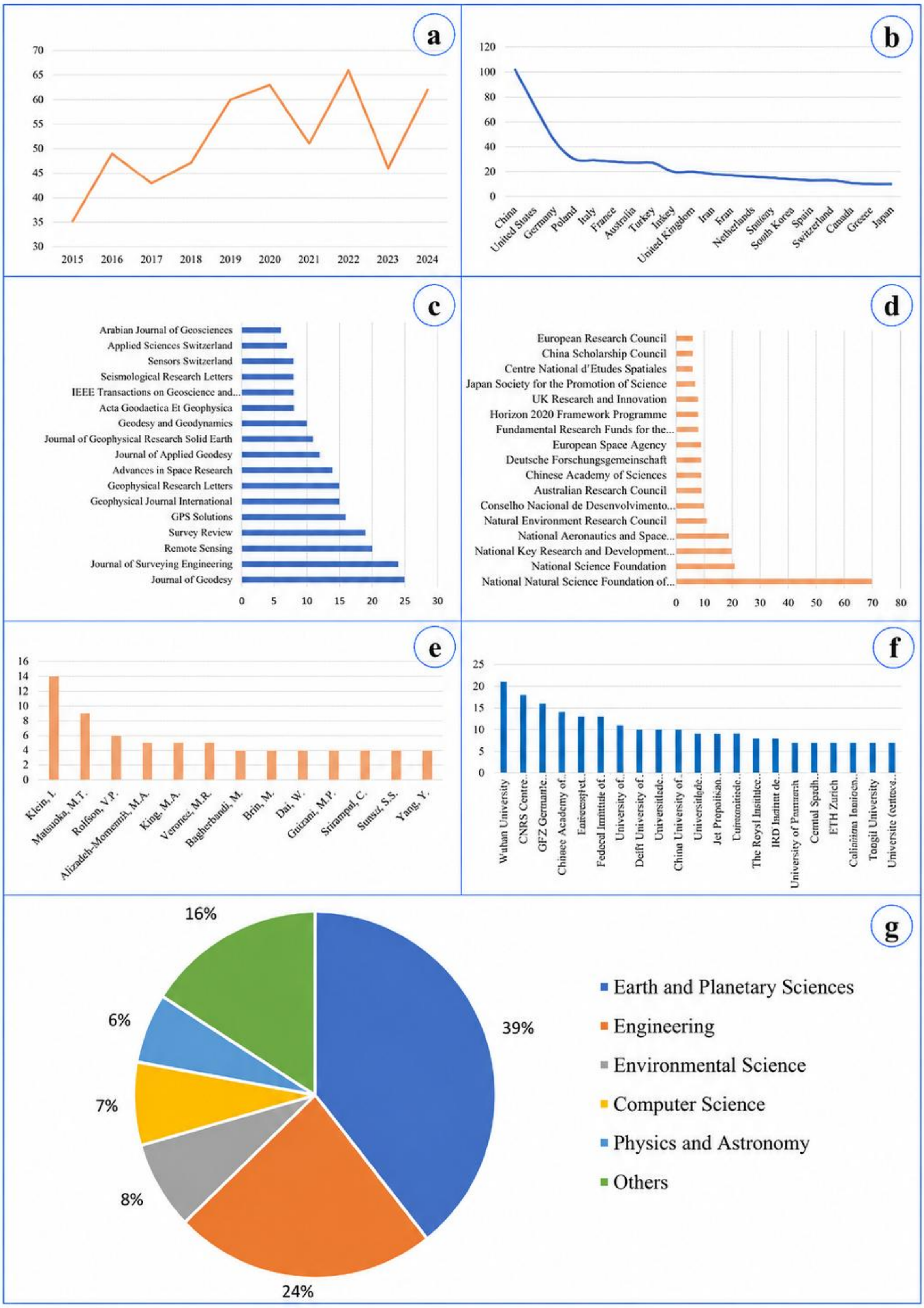

Figure 3. Research structure in the field of the optimisation of geodetic networks based on 522 publications during the period 2015–2024: (a) Evolution of publications during the decade 2015 - 2024; (b) Leading countries of publication; (c) Publications classified by domain; (d) Funding sponsors; (e) Most productive authors; (f) Influential affiliations in the investigated field; (g) Discipline areas of the selected publications.

Regarding authorship, prominent contributors include Klein, Matsuoka and Rofatto, each credited with 6-14 publications (Figure 3e). In terms of institutional productivity, Wuhan University (China) is the most active institution, with over 20 articles, followed by leading centres such as CNRS - Centre National de la Recherche Scientifique (France), GFZ – Helmholtz Centre for Geosciences (Germany), and the Chinese Academy of Sciences (China) (Figure 3f).

Disciplinary distribution indicates that the majority of research is concentrated in Earth and Planetary Sciences (39%), followed by Engineering (24%), Environmental Sciences (8%), Computer Science (7%), and Physics and Astronomy (6%), while other areas collectively account for 16% (Figure 3j). This distribution underscores the multidisciplinary nature of CORS optimisation research, demonstrating strong links not only with geodesy, but also with computer science, engineering and environmental studies.

The bibliometric evidence confirms that the field is strongly supported by national grants and international research programmes. Leading institutions and researchers are increasingly applying Voronoi polygons, geodetic buffering, multi-GNSS integration and artificial intelligence approaches to improving network efficiency. The results suggest that the field is evolving in a multidisciplinary direction, with future research expected to focus on 3D coverage modelling, IoT integration and smart city infrastructure applications.

From a critical perspective, the bibliometric results show that the field is advancing rapidly but remains unevenly developed. The dominance of a limited number of countries and institutions indicates that current optimisation approaches are strongly shaped by region-specific technological capacity, data availability and funding structures. This limits the direct transferability of these methods to data-constrained regions such as Central Asia. In addition, although advanced optimisation algorithms and multi-GNSS approaches are increasingly represented in the literature, many studies remain simulation-based and provide limited validation using actual observational GNSS data. Therefore, a key research gap lies in connecting theoretical network optimisation with practical, region-specific performance evaluation. This gap justifies the use of simplified GIS-based spatial assessment as an initial planning tool, while also highlighting the need for future studies based on empirical GNSS observations, network geometry metrics and accuracy validation.

Overall, the bibliometric results indicate a growing and increasingly multidisciplinary research field, with strong contributions from leading countries, institutions and journals. These general patterns provide a foundation for a more detailed thematic analysis of methodological approaches, which is presented in the following section (3.2).

3.2. Analysis of the thematic literature

3.2.1. Geodetic Network Design and Optimisation

In recent years, the challenges of second-order design (SOD) and first-order design (FOD) have shifted from “theoretical best” configurations toward algorithms that account for practical constraints. Automated hybrid approaches that incorporate real measurement conditions ,such as the number of repetitions with total stations and logistical limitations of time and travel, have demonstrated the ability to achieve required accuracy with a minimum number of observations (Michal & Štroner, 2024). In SOD applications, a comparison of Hooke-Jeeves and simulated annealing methods demonstrated that Hooke–Jeeves was more suitable due to its flexibility in accommodating field constraints (Odziemczyk, 2024). In cost-oriented FOD, combining simulation with sequential evaluation has been shown to significantly reduce the number of observations (Postek, 2021).

For CORS/RTK network establishment, metaheuristic approaches have proven effective. A memetic algorithm provided superior results in selecting optimal CORS station locations compared to classical methods (Tang, 2015). Similarly, particle swarm optimization (PSO) (Farhan *et al.,* 2022) and the butterfly optimization algorithm (BOA) (Odam *et al.,* 2023) have demonstrated millimetre- to centimetre-level improvements in real networks such as the Nile Delta and GPS test networks. In route optimisation problems analogous to the traveling salesman problem (TSP), scheduling algorithms have been applied to shorten measurement campaigns (Bartonek *et al.,* 2017; Bostanci & Karaağaç, 2019). In geodetic tunnel networks, predictive models have reduced collision errors to as low as 3.5 cm (Savanovic *et al.,* 2015). On a larger scale, identifying where densification is required in existing networks has also been addressed using optimisation criteria (Sathiakumar *et al.,* 2017).

Satellite selection has emerged as another critical area of optimisation. Comparative studies of ABC, ACO, PSO and SA methods, based on 24-hour observations, concluded that artificial bee colony (ABC) is the most practical due to its ease of parameter tuning (Alluhaybi *et al.,* 2024).

Even in combinatorially explosive scenarios, such as selecting 15 satellites out of 31, the method achieved 100% accuracy. Related studies further indicate that reducing the number of connecting vectors does not significantly lessen positioning accuracy (Kudas & Wnęk, 2020).

3.2.2. Atmosphere (Troposphere/Ionosphere) and Water Vapour: GNSS-Based Modelling

At low latitudes, TEC variability is particularly high. A hybrid WOA-CNN-LSTM model (Whale Optimization + deep sequential learning) applied in the Sichuan-Yunnan region (2015–2019) achieved RMSE ≤ 2.75 TECu during storm years and ≤ 0.74 TECu during quiet years (Li *et al.,* 2024). Similarly, a CEEMDAN + ARIMA + GWO-LSTM hybrid decomposed PWV time series into multiple frequency components, selecting tailored models for high- and low-frequency signals, improving prediction accuracy by 20–30% (Xiao *et al.,* 2022). Machine learning approaches such as multicore SVM and PSO-LSSVM have further enhanced the stability of ZTD estimation and meteorological parameter retrieval (F. Yang *et al.,* 2021; Zhang *et al.,* 2016).

In tomography, optimising mapping functions and using unconstrained inversions significantly reduced errors compared with radiosonde observations (Miranda & Mateus, 2022). A seven-month experiment in the Amazon confirmed that boundary condition optimisation ensures stable quasi-online inversions (Miranda *et al.,* 2023). For GNSS + GIM data fusion, methods such as IONOLAB-MAP and CIT-based on kriging, model assimilation and optimised semivariograms-produced highly accurate regional TEC maps (DeviRen & Arikan, 2018; Tuna *et al.,* 2015). Alternative strategies, such as wavelet-based neural networks combined with PSO, also demonstrated regionally high accuracy compared with spectral or multilayer architectures (M. R. Ghaffari Razin & Voosoghi, 2016; M.-R. Ghaffari Razin & Voosoghi, 2017). Satellite assimilation studies have validated OMI TCWV v4 against GPS/SSMIS data, showing that proper cloud filtering significantly improves assimilation performance (H. Wang *et al.,* 2019).

In the InSAR domain, Sentinel-1 time-series data captured the 2018 Boso slow-slip event, estimating a slip of ~5 cm and Mw ~6.4. Regularisation using the L-curve criterion was shown to enhance spatial resolution relative to GNSS-only solutions (Kinoshita & Furuta, 2024).

3.2.3. Robust adjustment and resistance to faulty observations

Under conditions of colour deficiency or multiple gross errors, global L1, iterative reweighting and exhaustive search approaches have shown success in various scenarios, although computational complexity grows rapidly (Baselga *et al.,* 2020). In rank-deficient GNSS networks, an improved grey wolf algorithm enabled direct L1-norm optimisation, avoiding LP-related difficulties and proving effective on both real and simulated datasets (Mahboub *et al.,* 2024).

3.2.4. Computational efficiency and new optimisation paradigms

In multi-core implementations of normal equations, block parallelism and cache-traffic optimisation can accelerate precise orbit determination (POD) computations by up to a factor of three (Chen *et al.,* 2022). The information filter has demonstrated up to ~50% faster performance than the conventional Kalman filter in certain GNSS differential scenarios (Zheng *et al.,* 2019). For complex multimodal objective functions, deep Gaussian processes (DGPs) with multitask/transfer learning have provided improved accuracy in auto-tuning (Łuszczek *et al.,* 2023). Furthermore, the combination of Bayesian optimization (BO) and DGP was shown to yield superior results in spectral domains compared to traditional methods, particularly in terms of accuracy and uncertainty quantification (Garbuglia *et al.,* 2023). In distance geometry problems with discretisation, integer programming/constraint programming (IP/CP) and hybrid decomposition approaches significantly outperformed classical MIN-DOUBLE solutions (MacNeil & Bodur, 2022).

3.2.5. Applied studies and monitoring

Comparisons between UAV-RTK and PPK have revealed strong sensitivity to surface type; vertical (Z) errors were found to be low over ground, road or bush surfaces, but high in forested and shaded areas (Eker *et al.,* 2021). Using Houston extensometers, seasonal subsidence–heave cycles in the range of 2-4 cm have been documented (G. Wang, 2023). For seafloor geodesy, practical guidelines have been provided for model errors related to station shell, track geometry and sound speed (Y. Yang *et al.,* 2020). In addition, a 3D finite-element (FE) model of the L'Aquila earthquake, integrating InSAR and GPS observations, explained deformation and stress fields more effectively than the classical Okada model (Castaldo *et al.,* 2018).

In summary, the studies reviewed demonstrate a wide range of methodological approaches in geodetic network design and GNSS optimisation, with a strong focus on advanced modelling and algorithmic solutions. However, a gap remains between these theoretical developments and their practical application, particularly in data-limited environments.

3.3. Bibliometric Insights and Research Trends in CORS Network Optimisation

The bibliometric analysis reveals a clear and sustained increase in scientific research activity related to the optimisation of CORS networks. Based on the reviewed literature, a marked growth in publications has been observed, particularly after 2015, reflecting the rising global demand for high-precision geodetic infrastructures. This trend is closely associated with the rapid advances in GNSS technologies, the increasing reliance on real-time positioning systems, and the broader development of the digital economy.

The analysis further indicates that studies can be broadly categorised into several major methodological groups. The first includes studies grounded in classical geodetic network design, primarily based on least squares adjustment techniques. The second group encompasses research employing optimisation algorithms, in which methods such as genetic algorithms, particle swarm optimization (PSO), and simulated annealing are widely applied. The third consists of GIS-based and spatial analysis approaches, which are mainly used for visualisation purposes and preliminary network assessment.

Despite the methodological diversity, an important trend emerges from the bibliometric findings: while a significant portion of the literature relies on advanced mathematical and optimisation-based models, their practical implementation remains limited, particularly in developing countries. This limitation is often attributed to the lack of high-quality observational data, insufficient technical infrastructure, and the challenges associated with applying complex models under real-world conditions.

In addition, GIS-based approaches appear to be relatively underrepresented and are typically employed as simplified tools for initial evaluation. This indicates the presence of a gap between theoretically rigorous optimisation models and their practical, region-specific application. Such a discrepancy represents a critical challenge to the effective planning and deployment of CORS networks.

This study specifically addresses this research gap by integrating insights derived from bibliometric analysis with a simplified GIS-based spatial evaluation framework. The proposed approach does not aim to replace rigorous geodetic modelling, but rather to provide a practical and scalable conceptual tool that supports preliminary planning and decision-making processes, particularly in data-constrained environments.

3.4. Case Study (Republic of Uzbekistan)

The Uzbekistan case study is presented to demonstrate the application of simplified spatial analysis methods in a data-constrained national context. The planning and expansion of the CORS network in Uzbekistan are influenced by several local factors, including pronounced relief variability, extensive desert and semi-desert areas, uneven telecommunication and power infrastructure, and cross-border coordination requirements with neighbouring countries. Seasonal and cyclic ionospheric variations may also affect long-baseline RTK and VRS solutions. However, these factors are discussed here as contextual constraints only; the analysis evaluates spatial coverage and does not quantify positioning accuracy or GNSS network performance.

In the republic, very few scientific studies have been conducted in this field, which can be attributed to the scarcity of open data. Among them, Ruziev and et al. studied GNSS (global navigation satellite system) technology in the context of constructing a geodetic network in the capital of Uzbekistan and showed that no systematic work had previously been conducted on its reconstruction and development (Ruziev *et al.,* 2024). In addition, this system involves appropriate organisation of the geodetic satellite network, as well as the development of a unified innovative system for state cadastres and real estate registration (Madimarova *et al.,* 2024). The present GNSS network and its data constitute the main subject of Fozilova's research, which emphasises that efforts are underway to establish a modern network in Uzbekistan's geodesy sector. The primary-level networks and data transmission stations were nearly completed (Fazilova, 2017). Furthermore, as a result of research conducted by relevant state institutions, a web geoportal has been developed (Ndirangu *et al.,* 2020).

Available open materials and practical reports often assess coverage based on Euclidean distance circle buffers, while coverage maps at the regional level, inter-station baseline length statistics, or PDOP scenarios are rarely presented (Prochniewicz *et al.,* 2020). In addition, the placement problem is frequently addressed using simple statistical analysis approaches based on expert judgment.

As a result, investment decisions face difficulties in providing a precise, quantitative answer to the question: "In which area will the installation of a certain number of stations yield the greatest benefit in terms of coverage and service quality?" Moreover, in recent years, ArcGIS has been successfully applied in geovisual monitoring and decision-making, owing to its capability to integrate real-time data and interactive maps (ESRI, 2023).

The objective of our study is to evaluate the coverage of the existing CORS network in Uzbekistan using a geodetic approach (based on the WGS84 ellipsoid) through data collection, pre-processing, spatial analysis, visualisation, and the creation of a management geoportal. The study further aims to analyse the spatial distribution and service coverage of CORS stations; identify overlapping areas and uncovered zones based on 40 km buffer zones; and develop an interactive web map to present the results.

In conducting the research, the GIS (ArcGIS Pro 3.3.0) environment was utilised. Initially, the state boundary of the Republic of Uzbekistan, the provincial boundaries, and the boundary of the Republic of Karakalpakstan were included. A database of 132 CORS stations was compiled, of which 50 represented older (previously installed) stations and 82 were newly established ones. Separate layers (feature classes) were created for old and new CORS stations (Figure 4).

To distinguish between old stations (shown in blue) and new stations (red), thematic symbology was applied (Figure 4). Buffer zones were displayed in transparent colours to represent service coverage. National boundaries were added as a layer, enabling the analysis of CORS coverage in relation to both the country's borders and administrative regions.

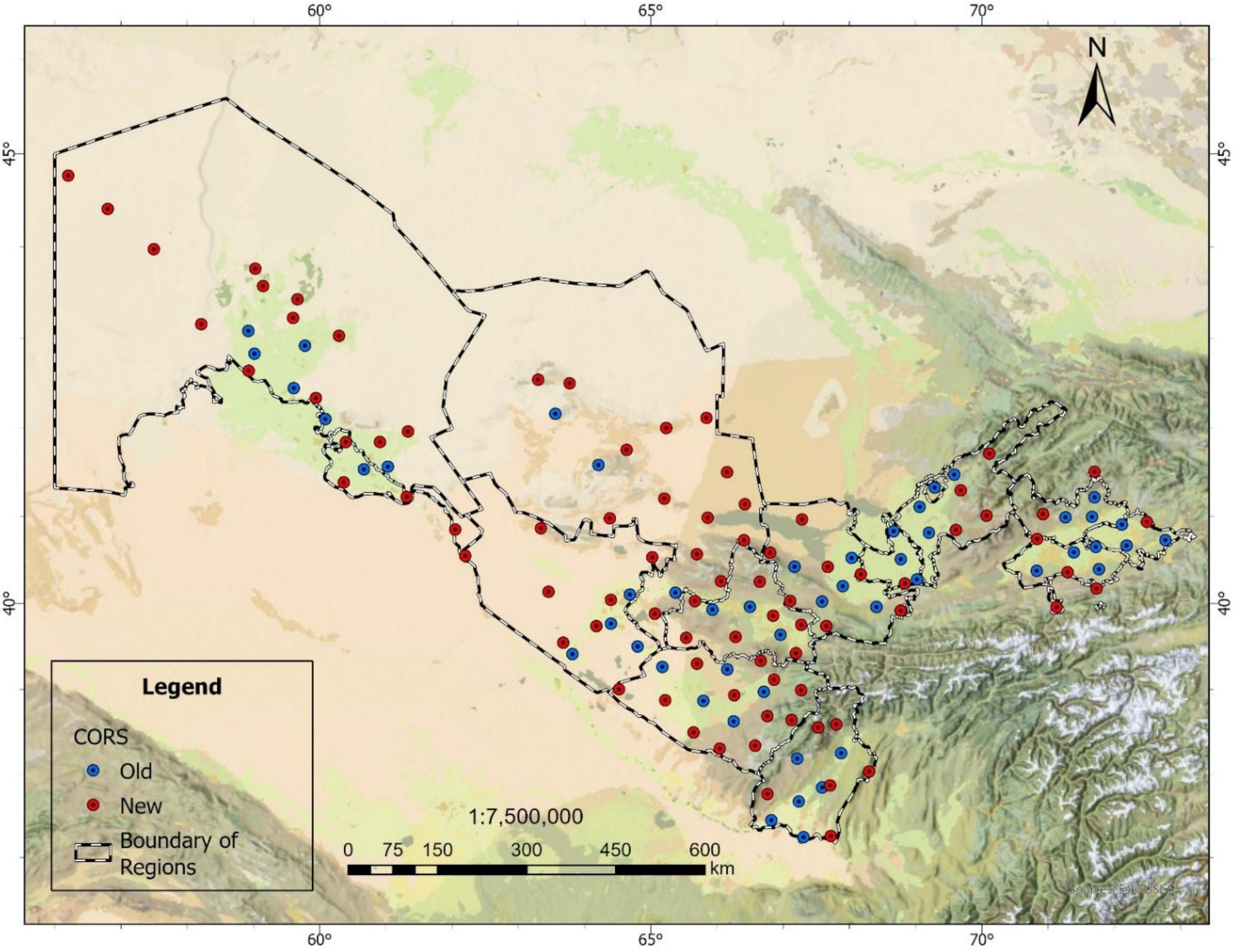

Figure 4. General CORS Locations.

To evaluate the service coverage of the CORS network, circular buffer zones with radii of 40 km, 50 km and 60 km were generated around each station (Figure 5). These distances represent commonly used baseline lengths in GNSS network design. Shorter baselines are generally associated with more stable positioning performance due to the higher spatial correlation of atmospheric errors, whereas larger distances increase coverage, but may lead to reduced positioning reliability (Wanninger, 2002).

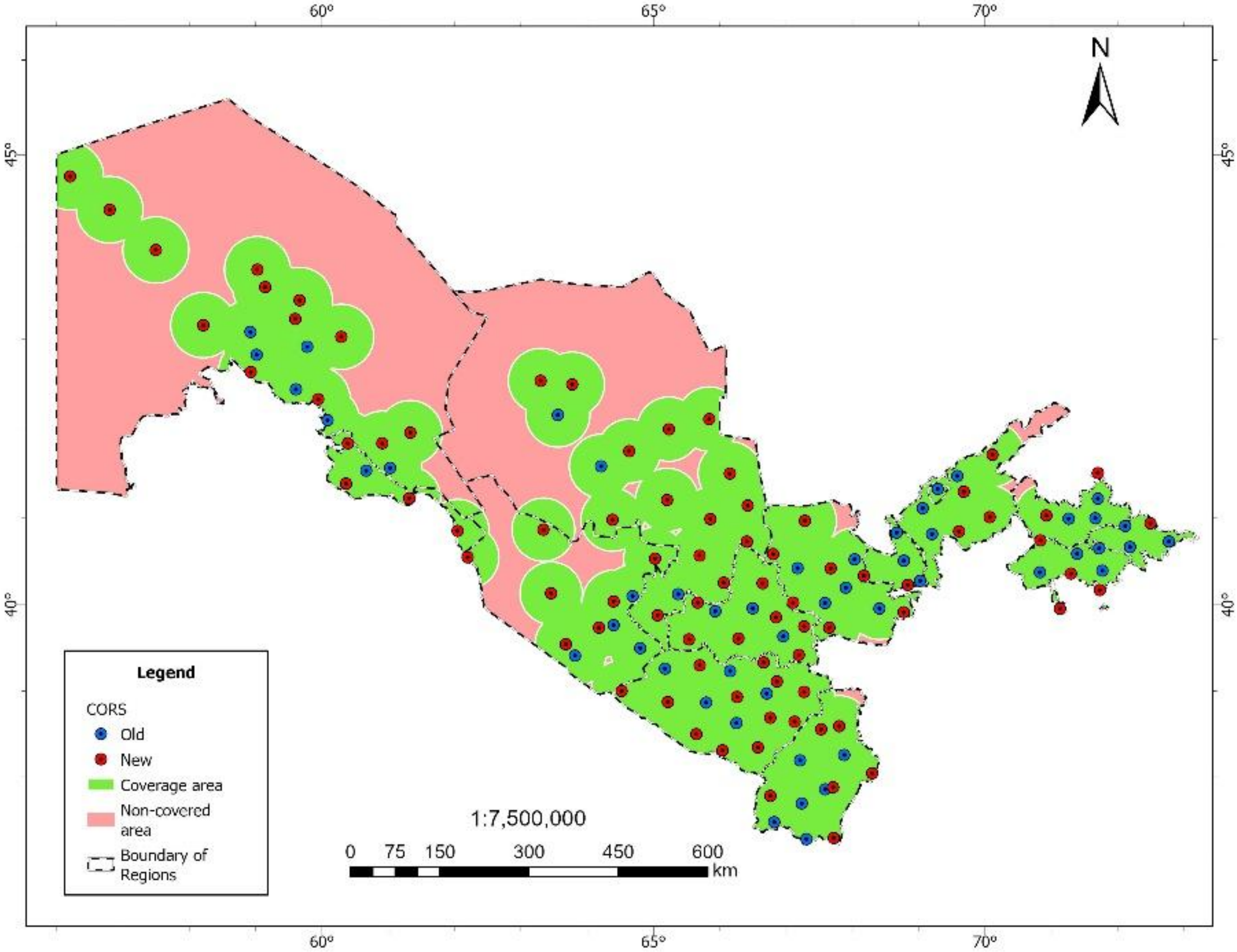

Figure 5. CORS Coverage Areas.

The buffer analysis was performed in the ArcGIS Pro environment (ESRI, 2022), in which coverage areas were delineated for each scenario and the total coverage area was calculated (Table 1). In addition, the degree of overlap between buffer zones was analysed to identify redundant coverage and uncovered regions. These uncovered areas were considered priority zones for the installation of new stations.

Table 1. CORS Network Coverage by Buffer Distance Across Regions of Uzbekistan.

Region	Total Area (km²)	Coverage (60 km)	Coverage (50 km)	Coverage (40 km)
Andijan Region	4,259.67	4,259.67	4,259.62	4,202.77
Bukhara Region	40,069.99	32,249.00	27,640.94	21,114.57
Fergana Region	6,740.28	6,740.28	6,707.45	6,587.27
Jizzakh Region	21,006.01	20,462.64	19,521.14	17,417.01
Kashkadarya Region	28,496.88	28,496.88	28,476.08	27,707.17
Khorezm Region	6,348.94	6,348.86	6,225.67	5,925.19
Namangan Region	7,422.08	7,177.23	6,858.16	6,522.80
Navoi Region	110,828.29	61,717.66	52,892.33	41,619.77
Republic of Karakalpakstan	166,021.98	54,434.71	44,843.72	34,766.81
Samarkand Region	16,810.07	16,810.07	16,810.07	16,743.56
Syrdarya Region	4,248.42	4,248.42	4,248.42	4,220.46
Surkhandarya Region	20,115.32	19,959.19	19,615.11	18,561.29
Tashkent City	438.67	438.67	438.67	438.67
Tashkent Region	15,093.97	13,734.44	13,209.27	12,306.52
Total	447,900.56	277,077.72	251,746.67	218,133.86

At the regional level (Table 1), the analysis shows that areas with a high density of stations, such as Tashkent city, the Fergana Valley (Andijan, Fergana, Namangan), and the Syrdarya corridor, as well as large parts of the Samarkand, Jizzakh and Surkhandarya regions, remain well covered across all scenarios. For example, in the Jizzakh region, only 1.18 × 10^3 km^2 remains uncovered out of a total area of 19.8 × 10^3 km^2.

In contrast, the largest uncovered areas are in the Republic of Karakalpakstan (≈112.2 × 10^3 km^2), the Navoi region (≈54.3 × 10^3 km^2) and the Bukhara region (≈11.1 × 10^3 km^2). Meanwhile, coverage gaps in Kashkadarya (≈6.9 km^2), Fergana (≈15.4 km^2), Khorezm (≈67 km^2) and Surkhandarya are minimal. These results indicate that the CORS network is relatively dense in populated and economically active regions, while coverage remains sparse in desert and semidesert zones such as the Ustyurt Plateau and the Kyzylkum Desert.

The comparative analysis demonstrates a clear relationship between buffer distance and coverage extent (Table 2). Under the 40 km scenario, the total coverage area is approximately 218,133.9 km^2, corresponding to 48.70% of the country's territory. Increasing the radius to 50 km expands the coverage to 251,746.7 km^2 (56.21%), while the 60 km scenario reaches 277,077.7 km^2 (61.86%). These values should be interpreted strictly as spatial coverage indicators. They do not represent positioning accuracy, network reliability or GNSS performance, as no observational GNSS validation or accuracy assessment was conducted for the study.

Table 2. Coverage Efficiency by Buffer Distance.

Buffer Distance	Area Covered (km^2)	Coverage (%)	Interpretation
40 km	218,133.86	48.70%	Conservative coverage scenario
50 km	251,746.67	56.21%	Intermediate coverage scenario
60 km	277,077.72	61.86%	Extended coverage scenario

The spatial variability of coverage is further illustrated in Figure 6, which presents the coverage area and coverage efficiency for each region based on the 40 km buffer scenario. The results show that regions such as Navoi, Karakalpakstan and Kashkadarya have large coverage areas but relatively lower efficiency, reflecting sparse station distribution over extensive territories. In contrast, regions with compact territories and dense station networks, such as Tashkent city, Andijan and Sirdarya, exhibit high coverage efficiency despite their smaller absolute coverage areas. This pattern highlights the uneven spatial performance of the network and emphasises the importance of considering both coverage extent and efficiency in network evaluation.

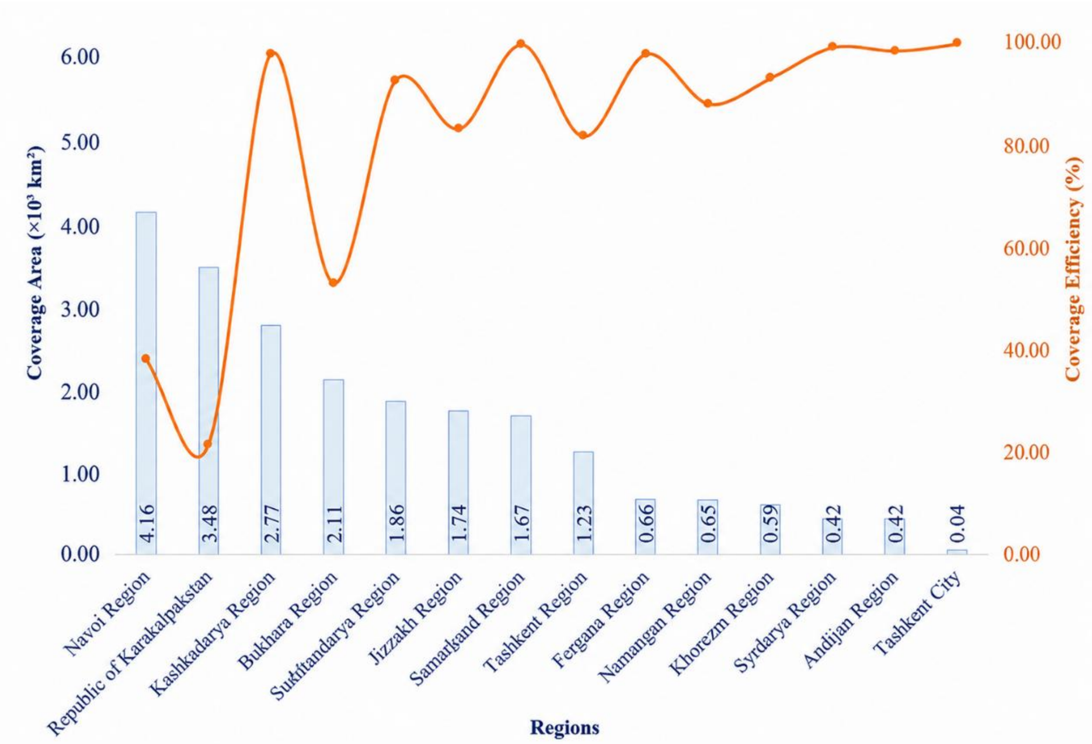

Figure 6. Area Coverage of the CORS Network Based on a 40 km Buffer Approach.

Furthermore, the analysis of station characteristics shows that older stations are mainly concentrated in the south-eastern regions of the country and have been in operation for many years. In contrast, newly installed stations were deployed more evenly across the territory during the modernisation process, thereby expanding overall coverage. Statistical analysis indicates that the average elevation of older stations is 604.5 m, whereas new stations are located at an average elevation of 885.5 m. The number and spatial distribution of new stations have contributed to a more balanced national network configuration.

Overall, the results (Table 2) highlight a trade-off between coverage and baseline distance. Larger buffer radii increase spatial coverage; however, they do not directly correspond to improved GNSS positioning accuracy, which also depends on additional factors such as atmospheric conditions, signal quality and network geometry. In this context, the range of 40–50 km may be considered a balanced compromise between coverage and potential positioning performance, although this conclusion should be interpreted with caution.

It is also important to note that most of the uncovered areas correspond to desert regions. Currently, these lands are gradually being developed and integrated into the national economy. Therefore, in the near future, the establishment of additional CORS stations in these regions will become necessary.

Finally, it should be emphasised that the analysis is based on a simplified geometric buffer approach and does not account for key GNSS error sources such as ionospheric and tropospheric effects, multipath, signal quality or network geometry (e.g., PDOP). Therefore, the results should be interpreted as a preliminary spatial assessment rather than a comprehensive geodetic optimisation.

3.5. Discussion

In recent years, the demand for high-precision data in geodesy, remote sensing and monitoring technologies has increased significantly. This growing need has stimulated the rapid development of GNSS, CORS and InSAR technologies. Research conducted across various domains (Benoit *et al.,* 2015; Bevly *et al.,* 2016; C. Yu *et al.,* 2018) has broadly highlighted the potential applications of these technologies and demonstrated their importance at the intersections of multiple scientific disciplines.

Building on the considerations outlined in the introduction, the study results support the view that inter-station spacing remains a critical factor in CORS network performance. The spatial analysis indicates that moderate station spacing provides adequate territorial coverage in many regions of Uzbekistan; however, noticeable gaps persist, particularly in the western parts of the country. This suggests that, while commonly recommended spacing ranges can serve as a useful reference, their practical effectiveness is strongly influenced by regional conditions such as terrain, atmospheric variability and infrastructure availability. Therefore, optimisation strategies should be adapted to local characteristics rather than relying on uniform spacing assumptions. Recent studies in Turkey and Malaysia and global analyses emphasise the importance of considering atmospheric effects, network geometry and technological advancements when determining the most effective CORS configuration (Feng & Li, 2008; Gökdaş & Özlüdemir, 2022; Pipitone *et al.,* 2023; Rahmani *et al.,* 2023; H. Yu *et al.*, 2020).

Accordingly, our thematic analysis examined 53 selected articles, with closer scrutiny of the five most highly cited. This citation-weighted focus is deliberate: the most cited works define the methodological baseline against which regional adaptations are tested, making them the appropriate reference points for assessing transferability to Uzbekistan's specific topographic, atmospheric, and infrastructural conditions.

These works converge on a single conclusion: high-precision geodetic monitoring is not constrained by any one limitation but by a trilemma of accuracy, infrastructure, and cost, where optimising one dimension typically presses on the others. The generic atmospheric correction model of Yu et al. (2018) defines the accuracy frontier, i.e., adapting tropospheric correction to terrain and atmospheric conditions yields strong results for deformation monitoring in seismically active regions, but precisely because it is tuned to local atmospheric behaviour, it resists direct transfer and would demand region-specific recalibration across Uzbekistan's arid lowlands and steep mountain gradients. Bevly et al. (2016) shift the binding constraint from algorithm to infrastructure: their real-time GNSS/CORS work for connected and automated vehicles matters less as a transport result than as a demonstration that the value of geodetic precision is realised only through a dense, continuously operating reference network. Benoit et al. (2015) then address the dimension that determines whether either of the preceding strengths is deployable at all: their low-cost, high-frequency Geocube network attacks the affordability barrier, converting high-precision monitoring from a capability that exists in principle into one feasible in resource-constrained settings.

The overall conclusion of these three studies is that GNSS, CORS, and InSAR technologies extend beyond geodesy and are increasingly applied in the fields of transportation, environmental monitoring, construction and safety. Future research should focus on integrating current methods, merging various sensor networks, and improving real-time data flow. Introducing such integration in Uzbekistan and advancing research in this direction will form the foundation for a modern CORS system in the country.

The findings of this case study should be interpreted within the scope of several limitations. First, access to data from government institutions is restricted, as most domain-specific information is considered confidential. This limits the completeness and transparency of the analysis. Second, due to data confidentiality, many studies have lost their relevance and are not directly aimed at addressing the current challenges. Third, practical constraints of real-time monitoring systems, such as network latency, reliability of data transmission channels, and the long-term stability of equipment, have not been sufficiently explored in a number of experimental studies. Fourth, the number of scientific works specifically focusing on the selected region remains limited, while fifth, the findings highlight a common limitation in practice, where simplified approaches such as buffer analysis are used instead of rigorous geodetic network evaluation methods.

Based on the identified limitations, several practical and scientific priorities can be outlined for future research. Strengthening collaboration between academic researchers and industry stakeholders is essential to improve data accessibility and facilitate more efficient data exchange. In addition, expanding national research efforts on geodetic networks, particularly CORS stations, is important for advancing scientific understanding in the Republic of Uzbekistan. Furthermore, gradual expansion of the territorial coverage of CORS stations should be considered, with the long-term goal of achieving full national coverage. At the same time, studying international best practices for the efficient deployment of CORS stations and adapting them to local conditions will support more effective network development. Overall, these directions will contribute to improving the reliability, efficiency and sustainability of geodetic infrastructure in data-limited environments.

4. Conclusion

In conclusion, the study presents a structured bibliometric synthesis of research on the design and optimisation of CORS networks, highlighting the evolution of methodological approaches and current research trends. The analysis demonstrates that while classical geodetic models and modern optimisation algorithms are widely discussed in the literature, their practical implementation, particularly in data-constrained environments, remains limited.

Rather than conducting a full technical or performance-based evaluation of GNSS networks, the study has focused on identifying prevailing methodological directions and research gaps. In this context, the Uzbekistan example is presented solely as an illustrative case, in which a simplified GIS-based buffer analysis is applied to demonstrate how commonly used approaches in the literature can support preliminary spatial assessment. It is important to emphasise that this analysis reflects only coverage patterns and does not represent positioning accuracy, network performance or geodetic reliability.

From a practical perspective, the proposed conceptual approach can serve as an initial decision-support tool for CORS network planning in data-limited regions. Future research should focus on extending this framework by incorporating advanced methodologies, including network geometry analysis, stochastic modelling and accuracy validation, to support more robust and operational GNSS infrastructure development. Accordingly, the findings should be used as a preliminary planning reference rather than as evidence of operational accuracy. The main value of the study lies in linking bibliometric evidence with a practical spatial screening framework for identifying regions where further GNSS-based validation and network densification may be required.

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Author Contributions

Conceptualization: Norboeva, D., Inamov, A.; **methodology**: Norboeva, D., Khasanov, K.; **investigation**: Turaev, R., Inamov, A., Lapasov, J., Safaev, S.; **writing—original draft preparation**: Norboeva, D.; **writing—review and editing**: Khasanov, K.; **visualization**: Norboeva, D., Turaev, R. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflicts of interest.

Data availability

All data supporting the findings of this study were derived from publicly available literature and open-access geospatial datasets.

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